SLAC NATIONAL ACCELERATOR LABORATORY

Modeling the Optical PSF

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Introduction

The Dark Energy Survey (DES) is a 5000 sq. deg wide-field survey with the Dark Energy Camera that attempts to constraint the dark energy equation of state to high precision through a combination of weak gravitational lensing tomography and other astrophysical probes.

In order to do weak gravitational lensing, the shapes of galaxies must be extremely well measured. However, these shapes are modified by the Point Spread Function (PSF), which is affected by atmospheric seeing, telescope optics, and camera focus and alignment.

Current methods for handling the PSF involve empirical local (CCD-level) cartesian polynomial interpolations from observed stars to the measured galaxies. This method is borderline sufficient for current DES data, lacking for final DES observations, and grossly insufficient for the LSST era.

In wide-field surveys, the optical component of the PSF will vary with location on the focal plane in a complicated manner and will change due to misalignments of the camera with the telescope. Modeling the optical PSF provides a potential avenue for improving the interpolation of the PSF to galaxies by incorporating prior physical information.

Optical Model

The PSF is modeled as a pupil-plane Zernike polynomial expansion. The observed PSF is the result of propagating the pupil-plane (u, v) wavefront to the focal plane (x, y) via Fraunhofer diffraction:

$$I(x,y) \sim \left|\mathcal{F}\left\{P(u,v;\ x,y)e^{2\pi\imath W(u,v;\ x,y)/\lambda}\right\}\right|^2$$

Information about the obscuration of the pupil is encoded in Pupil P term, while the contribution of optical and atmospheric aberrations appear in the Wavefront W term. The wavefront is modeled as a sum of Zernike polynomials, where each polynomial corresponds to a classical optical aberration:

$$W(u,v;\ x,y) = \sum_i a_i(x,y)Z_i(u,v)$$

The optical contribution to the PSF is encoded in the coefficients of the Zernike polynomials. A baseline model is obtained by fitting defocused stars across several exposures. Misalignments in the Dark Energy Camera manifest as linear corrections with focal plane position to the baseline model. Thus we can represent the coefficients of the i-th Zernike polynomial for the j-th image at focal plane position (x, y) as:

$$a_{i,j}(x,y) = a_{i,0}(x,y) + \Delta_{i,j} + \Theta^x_{i,j}\ y + \Theta^y_{i,j}\ x$$

Note that misalignments of the Dark Energy Camera with the optics system only affect certain coefficients and introduce relations between coefficients. For example, if modifications to the baseline model on a per-image basis are due solely to misalignments, then:

$$\Theta^x_{6,j} = -\Theta^y_{5,j}\quad \Theta^x_{5,j} = \Theta^y_{6,j}$$

This physical model motivates our decision to fit some, but not all possible linear modifications to the baseline model.

Fitting the Focal Plane

The model is fit to the data by minimizing the least-squares difference between linear combinations of weighted adaptive second moments of model and data stars as measured by the *hsm* algorithm, which is an iterative method that uses an elliptical Gaussian weight to match to the measured image. The linear combinations correspond to the size and the unnormalized ellipticity:

$$e_0 = I_{xx} + I_{yy}\ ,\ e_1 = I_{xx} - I_{yy}\ ,\ e_2 = 2I_{xy}$$

The model allows for constant offsets in defocus, astigmatism, coma, and trefoil (Z 4–10) as well as linear shifts in astigmatism and coma (Z 5–8). The model also fits the Fried parameter, which characterizes the Kolmogorov kernel of the atmospheric seeing, and constant ellipticity modes. The fit is minimized using the MIGRAD algorithm in the MINUIT package, which implements a Davidon-Fletcher-Powell variable-metric method. A typical exposure has thousands of stars across the field of view, while our model has twenty-one free terms.

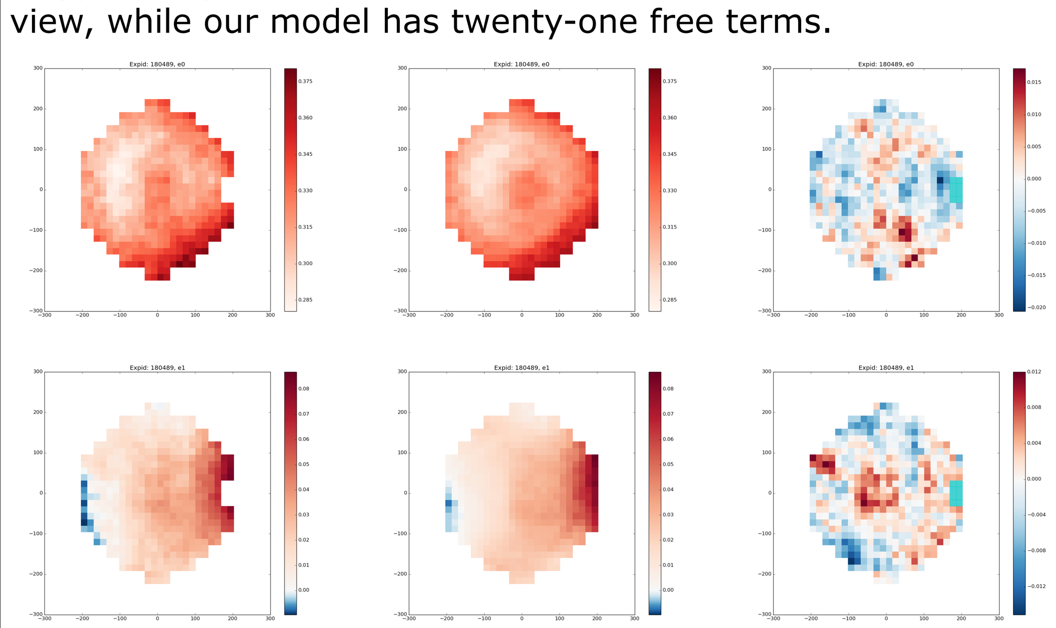

Figure 1. Example end result of fit on an image with significant tilt. Exposure data are on the left, model in the middle, and residual on the right. The top row fits the size, and the rest the two ellipticity parameters. Axes are focal plane position in millimeters, while the colors are the linear combinations of unnormalized second moments, in arcseconds squared.

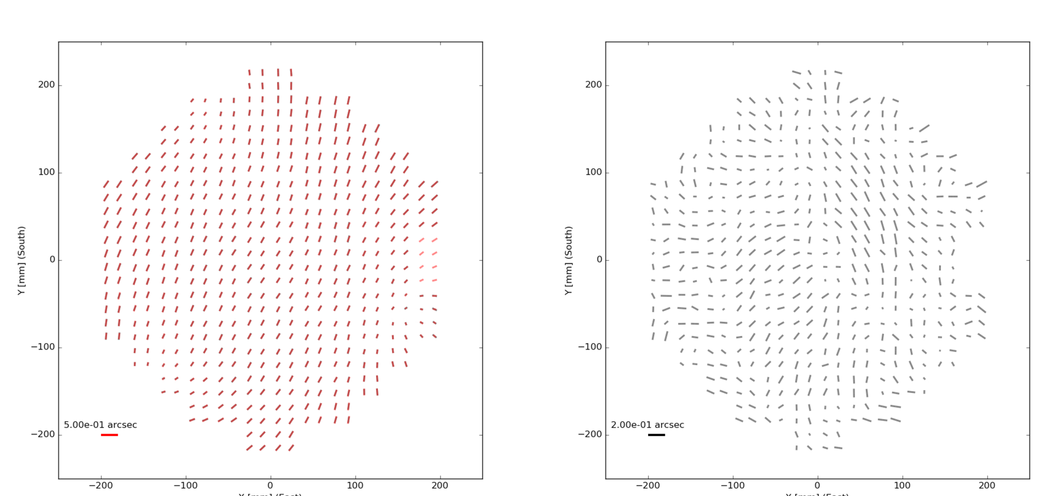

Figure 2. Another example fit, this time represented as a whisker plot of the second moments. The black whiskers on the left are the data, while the red are the model. On the right are the residual whiskers, calculated from the differences in moments. Notice the correlated structure in the residuals from aspects of the PSF that the model cannot capture.

Atmospheric Variations

An important check on the optics model is to examine the variability in the measurements of our baseline reference model. The baseline model is taken from several exposures of the defocused focal plane over several nights. Measurements across several nights indicate that the average model is stable, however, there are complex structures that appear in a given exposure which change on the timescale of an exposure. We have deduced that these must arise from atmospheric seeing.

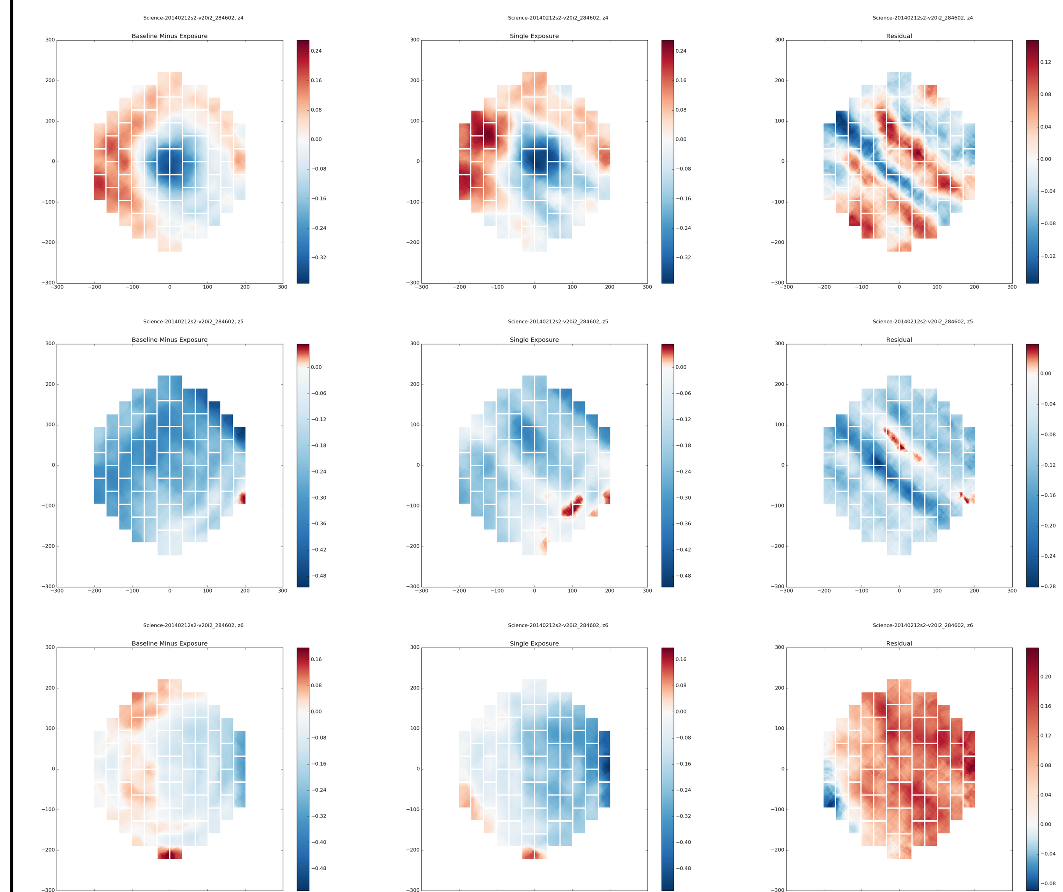

Figure 3. Measurements of the Zernike polynomial coefficients for defocus (top) and astigmatism-0 and -45. The left panels are the average baseline model from a single night excluding a single exposure, the central panels are the baseline model from only that single exposure, and the right panels are the residual differences. Note that the defocus row has been corrected to be in focus. The presence of such structures indicate that there is significant atmospheric variation over the course of the night.

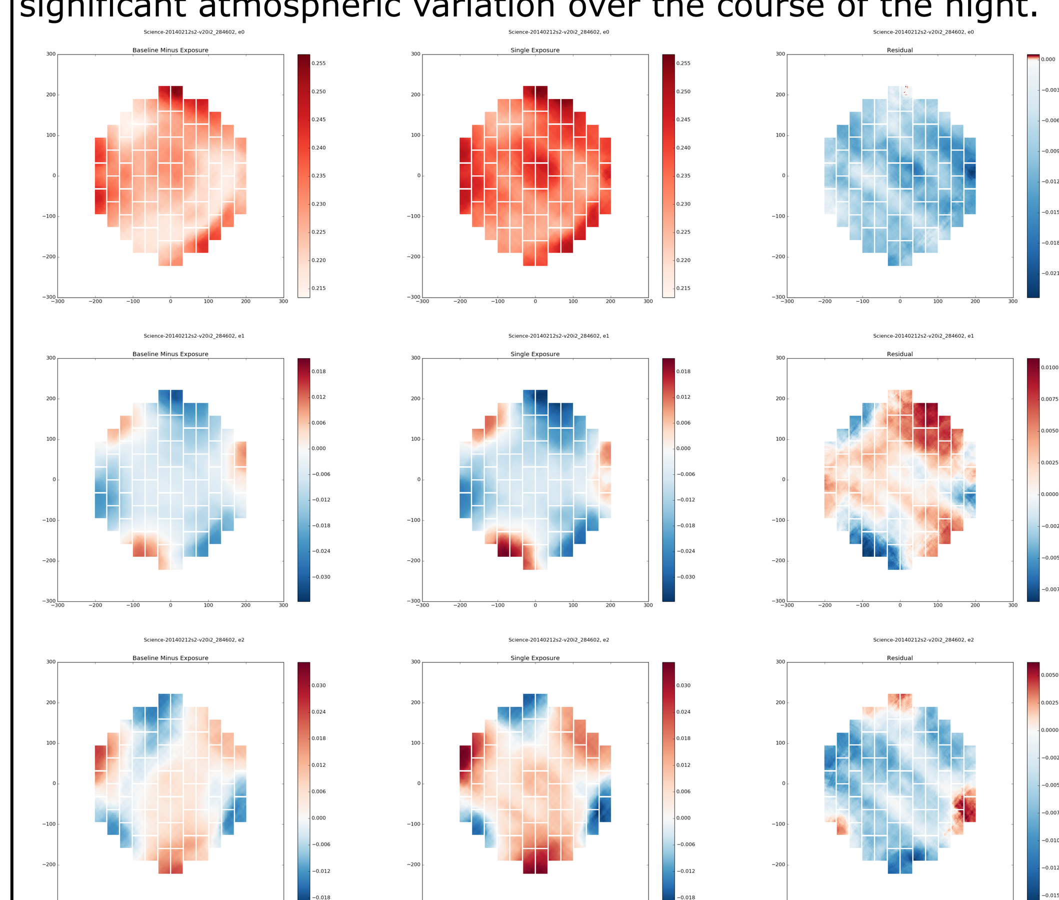

Figure 4. Like Figure 3, but now we show the predicted shape parameters *e0, e1,* and *e2,* that arise from stars generated using the average baseline or the single baseline model. The wave-like structures observed in Figure 3 propagate to our measurements of the PSF.

Fitting the Focal Plane?

Measurements of the Zernike polynomial coefficients in the baseline model indicate the presence of complex wavefront aberrations due to atmospheric or dome seeing. These patterns span several CCDs and are difficult to model with low-order cartesian polynomials. Further work is needed to determine the best methods of accounting for these structures.

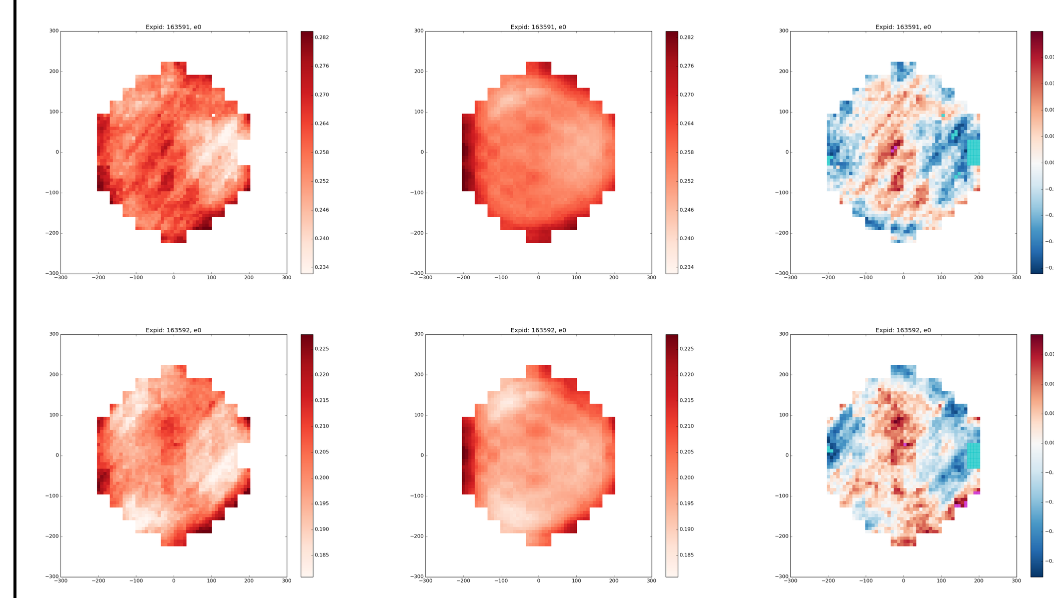

Figure 5. The size parameter e0 of two concurrent exposures marred by atmospheric seeing. The model is able to account for some of the structure, but the residuals show a varying wave-like structure similar to that in Figure 3 for which the model cannot account.

Conclusions

Current results on DES Science Verification Data are encouraging, if qualitative, for future PSF modeling.

The model is able to capture a wide variety of strikingly different ellipticity and size distributions across the focal plane.

Measurements taken from defocused images enable characterization of the PSF and the capture of the intricate distributions of optical aberrations.

Complex patterns of correlated aberrations due to atmospheric seeing may be leaking into both the baseline models and the exposures. These patterns have no fixed form on the focal plane, span several CCDs, and require more sophisticated techniques in order to handle.

By being able to model intricate patterns in ellipticity on the focal plane, we have shown that there is extant prior information on the PSF from our knowledge of the optics system that must be utilized to minimize PSF systematics.

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